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Experimental Determination of In Situ Utilization of Lunar Regolith for Thermal Energy Storage

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EXPERIMENTAL DETERMINATION OF IN SITU UTILIZATION OF LUNAR REGOLITH FOR THERMAL ENERGY STORAGE

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ABSTRACT

A Lunar Thermal Energy from Regolith (LUTHER) experiment has been designed and fabricated at the NASA Lewis Research Center to determine the feasibility of using lunar soil as thermal energy storage media. The experimental apparatus includes an alumina ceramic canister (25.4 cm. diameter by 45.7 cm. length) which contains simulated lunar regolith, a heater (either radiative or conductive), 9 heat shields, a heat transfer cold jacket, and 19 type B platinum rhodium thermocouples. The simulated lunar regolith is a basalt, mined and processed by the University of Minnesota, that closely resembles the lunar basalt returned to earth by the Apollo missions. The experiment will test the effects of vacuum, particle size, and density on the thermophysical properties of the regolith. The properties include melt temperature (range), specific heat, thermal conductivity, and latent heat of storage. Two separate tests, using two different heaters, will be performed to study the effect of heating the system using radiative, and conductive heat transfer. The physical characteristics of the melt pattern, material compatibility of the molten regolith, and the volatile gas emission will be investigated by heating a portion of the lunar regolith to its melting temperature (1435 K) in a 10^{-4} pascal vacuum chamber, equipped with a gas spectrum analyzer. A finite differencing SINDA model was developed at NASA Lewis to predict the performance of the LUTHER experiment. The analytical results of the code will be compared with the experimental data generated by the LUTHER experiment. The code will predict the effects of vacuum, particle size, and density has on the heat transfer of the simulated regolith.

1.0 INTRODUCTION

A solar dynamic power system that incorporates locally available resources can provide an extremely attractive system for lunar based thermal or electrical power. The production of oxygen on the moon is considered to be one of the primary processes for a permanent lunar base. This process requires significant quantities of both electrical and thermal energy at high temperatures. A solar dynamic power system is being proposed to supply this energy. Thermal energy storage is a critical element of a system that must store large quantities of heat during the eclipse portion of a lunar orbit (equivalent to 14 earth days).

An unique in-situ thermal energy storage approach was proposed by the University of South Florida under a NASA grant for a lunar based SD power system (figure 1).

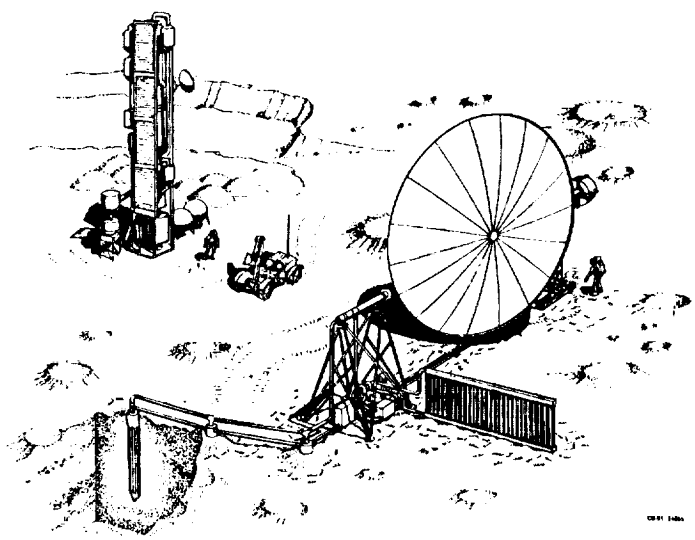

Figure 1 - Lunar Based SD Power System

The concept includes a 17.3 meter diameter solar concentrator focusing the incident solar flux into a heat receiver. A helium-xenon gas mixture is heated to a temperature of 1600 K within the heat receiver. During the on-sun phase of the lunar sun/shade cycle, a portion of the gas is pumped through the power conversion unit (PCU), i.e. Brayton or Stirling, to produce the desired electrical output. The remaining gas is pumped through a heat exchanger buried within the regolith where heat is transferred to the surrounding lunar regolith. This heat provides either latent or sensible storage to supply the required thermal power to the PCU during the lunar night, thus providing continuous power out of the alternator. The excess power is radiated to deep space by a radiator.

A solar dynamic (SD) power system that uses in-situ thermal energy storage will significantly reduce the requirements (i.e. weight, cost) of transporting thermal/electrical storage materials, and therefore reduce life cycle costs SD power systems. For example, the in-situ lunar thermal energy storage system could replace regenerative fuel cells for nighttime storage. The overall system specific mass of the proposed lunar based SD system that uses in-situ thermal energy has been projected to be 144 kg/kW for 25 kWe output, which is almost 1/3 the published values for existing alternatives, i.e. photovoltaic (PV) power system using regenerative fuel cells for storage [Crane, 1991].

A Lunar Thermal Energy from Regolith (LUTHER) experiment has been designed and fabricated at the NASA Lewis Research Center to determine the feasibility of using lunar soil as thermal energy storage media. Lunar regolith refers to the fine, loose, powder like soil found on the moon created by meteors pulverizing the moon rock for millions of years. Regolith particle sizes returned from Apollo missions range from 1.1 millimeters down to less than 44 microns.

The experiment will test the effects of vacuum, particle size, and density on the thermophysical properties of the regolith. The properties include melt temperature (range), specific heat, thermal conductivity, and latent heat of storage of the lunar regolith will be determined. Two separate tests, using two different heaters, will be performed to study the effect of heating the system through either radiative, or conductive heat transfer schemes. The first test will study the effects of heating the soil radiatively by locating a heater an inch away from the soil. In the second test, the regolith will be heated conductively by inserting a Borelectric boron nitride heater directly into the soil. The lunar regolith is chemically reactive, therefore material compatibility with a heat exchanger in contact with the soil may be a problem. The radiative scheme may prove to be a more effective method of transferring energy into the regolith.

The physical characteristics of the melt pattern, material compatibility of the molten regolith, and the volatile gas emission will be investigated by heating a portion of the lunar regolith to its melting temperature (1435 K). The test will take place in a 10^{-4} pascal vacuum chamber, equipped with a gas spectrum analyzer. The vacuum chamber is part of a facility dedicated to determine the feasibility of lunar regolith as a thermal energy storage material. The facility includes a room for data acquisition, and a laboratory where the tests will be performed.

A finite differencing SINDA model was developed at NASA Lewis to predict the performance of the LUTHER experiment. The analytical results of the code will be evaluated by the experimental data generated by the LUTHER experiment. The code will predict the effects vacuum, particle size, and density have on the heat transfer of the simulated regolith.

2.0 SIMULATED LUNAR REGOLITH

2.1 Description

Although the intrinsic lithologic and mineralogic diversity of the Moon is not as great as that of the Earth, considerable variability in the detailed textures, mineralogy, and chemistry has been found at the different Apollo and Luna sites [Taylor, 1975]. The University of Minnesota manufactures a simulated lunar regolith by plasma processing basalts mined in an abandoned quarry in Duluth, Minnesota. The mined material has a bulk chemistry and mineralogy that closely resembles the Apollo 11 mare basalts, soil sample 10084. [Goldich,1971; Weiblen, Gordon,1988] (table I).

Constituent	MLS-1 (avg)	Apollo 10084
SiO_2	43.86 %	42.55 %
TiO_2	6.32	7.71
Al_2O_3	13.68	13.47
FeO	13.40	15.16
Fe_2O_3	2.60	N/A
MgO	6.68	7.98
MnO	0.198	0.208
CaO	10.13	11.99
Na_2O	2.12	0.445
K_2O	0.281	0.147
P_2O_5	0.20	0.140
CO_2	0.0015	N/A

Table I - Element Chemistry of MLS-1 and Soil Sample 10084 [Weiblen,1988]

The major components of the processed minnesota lunar simulant (MLS-1) include fragments of rocks, minerals and glass, and agglutinates (fused granules of all of the other components) [Weiblen, 1990]. Figure 2 shows the MLS-1 delivered to NASA Lewis crushed ground and sieved to a particle size distribution between 300 - 500 microns in diameter.

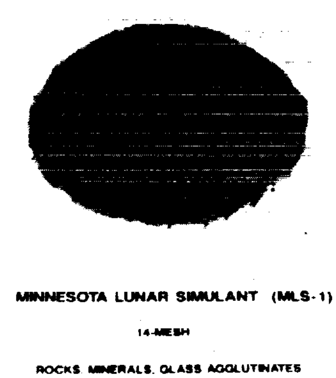

Figure 2 - Minnesota Lunar Simulant-1

100 kg of the Minnesota lunar simulant was delivered to NASA Lewis including fragments of rocks, minerals

and glass, and agglutinates. The MLS-1 was divided into three, 33 kg batches. Each batch of MLS-1 was crushed, ground and sieved to the following particle size distribution:

1) 1.1 mm and 800 microns.
2) 500 microns and 300 microns.
3) 80 microns and 44 microns.

2.2 Thermophysical Properties

A database was generated at NASA Lewis of thermophysical properties of lunar crystalline rocks for the Apollo 11 site (table II).

Melt Temperature (K)

The melting point of the soil was determined by a differential thermal analysis (DTA) at NASA Lewis. The melting point of a 177.2 mg sample was 1435 K, while the melting range is from 1430-1440 K. Prior to the DTA, a melt range over 50 degrees Kelvin was predicted due to the complex oxide composition of the lunar regolith.

The University of Arizona also determined the melting point of the simulated lunar regolith. The university placed two crucibles in a vacuum furnace, each filled with MLS-1 having the same composition. The university found the melting range to be between 1,290 and 1,573 K. Figure 3 shows the effect 10 K has on the melting of the simulated lunar regolith. The crucible on the left was resolidified after becoming liquid at 1,573 K, while the crucible on the right melted partially at 1,563 K.

Latent Heat of Fusion (kJ/kg)

Separate DTA runs calculated the latent heat of fusion for the MLS-1 to be on average 161.2 kJ/kg for an average sample mass of 33.2 mg.

The LUTHER experiment will determine the latent heat of fusion of the lunar regolith for larger sample sizes (20 kg), different particle sizes, and densities.

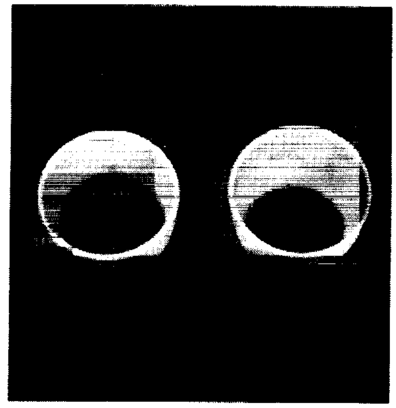

Figure 3 - 10 K Differential Melting of MLS-1

Thermal Conductivity (W/m K)

There is a great deal of uncertainty in the current values used for the thermal conductivity of the lunar regolith. Available thermal conductivity data for lunar samples is largely limited in temperature range of 300 and 450 K [Crane,1991]. Correlations have been developed to determine values of thermal conductivity for the lunar regolith in both the granular and consolidated forms: [Colozza,1991; Crane,1991]

$$k(T)_{granular} = 0.01281 + 4.431\times10^{-10}\ T^3$$

$$k(T)_{cons} = 3.615 - 0.00534\ T + 7.01\times10^{-6}\ T^2 - 5.8\times10^{-9}\ T^3 + 1.75\times10^{-12}\ T^4$$

It was partly the result of this uncertainty that the LUTHER experiment was proposed. Thermal conductivity has a significant impact on thermal analysis modeling the in-situ thermal energy storage. To minimize the heat losses to surrounding soil, a low

MINERAL	COMPOSITION	MASS PERCENTAGE	MELT TEMP. (K)	LATENT HEAT (KJ/Kg/K)	CONDUCTIVITY (W/M/K)	DENSITY (Kg/M^3)
Olivine Basalts						
- Forsterite	$2MgO\text{-}SiO_2$	0.77	1373	950	5.0	3035
- Fayalite	$2FeO\text{-}SiO_2$	0.10	1423	453	3.2	3764
Pyroxene Basalts						
- Enstatite	$MgO\text{-}SiO_2$	1.80	1448	699	4.4	2846
- Wollanstonite	$CaO\text{-}SiO_2$	43.13	1353	590	4.0	2846
- Ferrosillite	$FeO\text{-}SiO_2$	7.07	1423	699	4.2	2846
Plagioclase Basalts						
- Albite	$Na_2O\text{-}Al_2O_3\text{-}6SiO_2$	9.86	1398	208	2.3	2700
- Anorthite	$CaO\text{-}Al_2O_3\text{-}2SiO_2$	26.93	1373	270	1.7	2700
Opaque Basalts						
- Ilmenite	$FeO\text{-}TiO_2$	10.35	1363	650	2.6	3025

Table II - Properties of Lunar Crystalline Rocks thermal conductivity would be ideal. To exchange heat into and out of the soil, the ideal thermal conductivity will be high. It is critical for the thermal energy storage system to be designed around this conflict. A desired design would contain very dense, consolidated soil around the heat exchanger, while very loosely packed powder like regolith surrounding and insulating the system.

The LUTHER experiment will determine if these extrapolated correlations are valid within the specified temperature range (253-1573 K).

Specific Heat (kJ/kg K)

Available data for specific heat is also limited to the temperature range of 100 to 350 K [Yoder, 1976]. Through this range C_p is seen to increase from about 0.265 to 0.830 kJ/kg K for fine grained igneous rocks [Crane,1991]. A correlation developed by Colozza for an extrapolated higher temperature range was obtained as follows: [Colozza, 1991]

$$C_p = -1.8485 + 1.04741 \times \log(T)$$

Integrating the above equation over the temperature range of 253 to 1573 K yields a specific heat of 1.512 kJ/kg K.

Density (kg/m^3)

Density values for the granular lunar regolith are assumed to be between 1600-2000 kg/m^3. Values for the consolidated solid rock are between 3300 and 3400 kg/m^3 [Crane, 1991].

3.0 TEST HARDWARE

The LUTHER test apparatus was designed, fabricated and assembled at NASA Lewis. The test hardware consists of; a 998 alumina ceramic canister (25.4 cm. diameter by 45.7 cm. length) which contains the simulated lunar regolith, a boron nitride heater (either radiative or conductive), 9 heat shields, a heat transfer cold jacket, and 19 type B platinum rhodium thermocouples (figure 4).

Figure 4 - LUTHER Test Assembly

3.1 Test Canister

A 998 alumina canister was fabricated to the dimensions of 45.7 cm. long by 25.4 cm. outer diameter. The wall thickness of the canister is 0.635 cm.. The lunar regolith becomes extremely reactive at temperatures near the molten range due to the highly oxidative properties of the constituents. The high purity 998 alumina ceramic was selected for the canister, and thermocouple sheath materials due to material compatibility tests performed at NASA Lewis in a vacuum furnace. Figure 5 shows the alumina canister with the heater assembly installed.

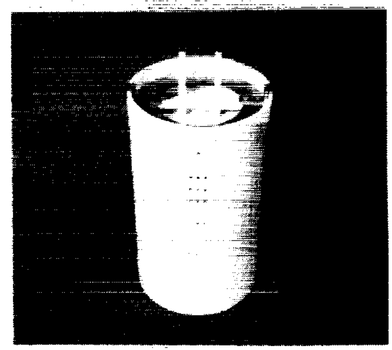

Figure 5 - Alumina Ceramic Canister with heater assembly

3.2 Heater Assembly

Two separate boron nitride Borelectric heaters were fabricated for the LUTHER experiment. Both heaters are rated at 100 Volts D.C., at 12 Amps. The maximum operating temperature of the heaters in a vacuum environment is 1773 K, which is well beyond the melting temperature of the regolith 1435 K. The first charge of the LUTHER test will be heated by a radiative heater (figure 6A). The test will study the melt pattern and thermal response of the regolith by melting a small 7.6 cm. diameter 'puddle' using radiative heat transfer from the source. The melt pattern and thermal response will also be investigated in the second set of tests, in addition freeze/thaw studies, by melting the majority of the soil using a conductive boron nitride heater (figure 6B).

Figure 6 - (A) radiative heater assembly - (B) conductive heater

3.3 Thermocouples

Nineteen type B platinum/rhodium thermocouples were presented to NASA Lewis. The thermocouples will be placed into 998 alumina closed-one-end sheaths that penetrate the cold jacket, 9 heat shield, and alumina canister (figure 7). The thermocouples were designed to be protected by the sheath as the lunar soil becomes molten. After multiple runs, the thermocouple remains preserved as the sheaths are discarded. The thermal lag of the sheath material will be incorporated into the data. The thermocouples are strategically located at positions both radially and axially that match up to the mesh network described for the finite difference SINDA thermal analysis.

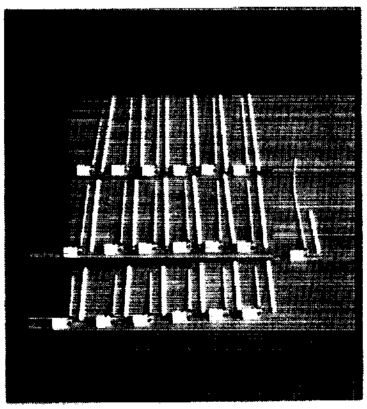

Figure 7 - Thermocouples

3.4 Heat Shields

A thermal analysis was performed on the LUTHER experiment at NASA Lewis to determine the number of heat shields required to insulate the experiment. A total of nine heat shields were fabricated at Lewis. The inner three shields, (top, bottom, and walls) were fabricated out of 0.05 cm. thick molybdenum due to the extreme temperatures. The outer six shields were fabricated out of 0.04 cm. thick stainless steel. The nine shields are illustrated in figure 8.

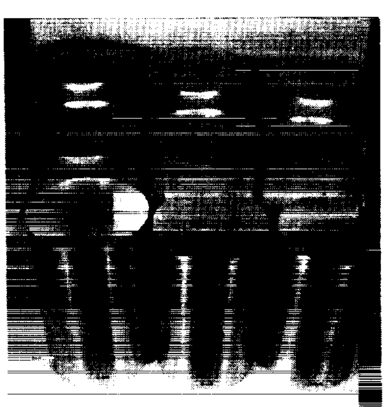

Figure 8 - Heat Shields

3.5 Water Cooling Jacket

A stainless steel jacket was fabricated to water cool the top, bottom and sides of the experiment. The overall dimensions of the jacket was 61 cm. L x 39.4 cm. O.D..

3.6 Safety Requirements

The LUTHER experiment was designed with two interlocks. An adhesive type K thermocouple was mounted to the outside of the glass bell jar. If the outside temperature of the bell jar goes over 373 K contact will be made and the power will be turned off. The second interlock is located in a flow switch. If the water stops flowing through the cooling-jacket, the power will also shut off.

4.0 TEST FACILITY

A facility was dedicated at NASA Lewis to test the feasibility of a lunar based in-situ thermal energy storage scheme. The facility includes a vacuum chamber, gas spectrum analyzer, 100 Amp / 100 Volt D.C. power supply, safety interlocks, shaker table, 2280A Fluke Logger, IBM 286 computer and printer, and a room for data acquisition and analysis. The vacuum chamber in the test facility is shown in figure 9.

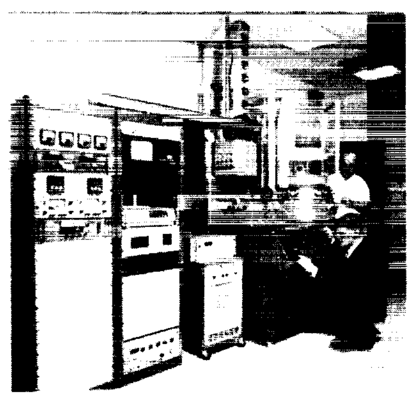

Figure 9 - Vacuum System in the Test Facility

The vacuum system includes an 45.7 cm. O.D. glass bell jar capable of pressures under $1x10^{-4}$ pascal. The vacuum chamber will be equipped with a gas spectrum analyzer to measure the atomic weight of the gases emitted as the regolith is heated. Safety interlocks were installed on the vacuum chamber to protect the system from potential failures.

A shaker table is required to tightly control the density of the lunar regolith. Initial tests show the regolith must be sieved between a minimal upper and lower particle size range to insure even particle size distribution within the test canister. With a large band of particle sizes, as the granular regolith is vibrated, the larger particles migrate to the top leaving an uneven particle size distribution.

5.0 EXPERIMENTAL PROCEDURE

5.1 Calibration of Equipment

The LUTHER experiment will be initially calibrated with granular aluminum oxide material. Aluminum oxide is used at NASA Lewis in fluidized beds. The granular oxide was provided in a 40-80 micron particle size distribution, with well defined thermophysical properties.

5.2 Test Matrix

Two separate test sequences will be implemented to test the thermophysical properties and melt characteristics of the simulated lunar soil using radiative and conductive heat transfer schemes.

The first test sequence will include the radiative heat transfer with a total of twelve tests. The test matrix will include testing two separate densities, three separate particle sizes, and two heat storage schemes for a total of twelve tests. The heat storage will include both sensible (1073 K maximum), and latent (1573 K maximum).

The second test sequence will be identical to the first with the exception of using conductive heat transfer, and melting a larger portion of the lunar regolith.

6.0 SINDA MODEL

A finite difference SINDA model has been developed at NASA Lewis to predict the performance of the LUTHER experiment. The SINDA model of the LUTHER experiment includes nodes equivalent to the thermocouple locations both axially and radially in a two dimensional plane. Initial results of the model predict that using the radiative heating scheme with thermal static control, approximately 5% (mass) of the soil will melt with a 1.2 kW input. The model has the flexibility of inputting different thermal conductivity and specific heat arrays.

7.0 SUMMARY

An experiment was designed, fabricated and implemented at NASA Lewis to determine the feasibility of using lunar regolith for solar dynamic thermal energy storage. There is a degree of uncertainty involved in the current correlations for thermal conductivity and specific heat of lunar regolith. The available data for thermal conductivity and specific heat is limited, and provided within limited temperature ranges (100-450 K). The current correlations were developed from extrapolating this available data out to the melting point of the lunar regolith (1435 K). The LUTHER experiment will provide data for the thermophysical properties of simulated lunar regolith from 295 - 1435 K. This data will be used to evaluate the validity of the extrapolations made, and improve upon the correlations for specific heat and thermal conductivity of the lunar soil.

The conditions for the LUTHER ground test experiment do not correlate exactly with the lunar case. The effect of gravity is the major difference, with the lunar gravity being 1/6 that of earth. The 1-gravity conditions of the ground test may impact the convective heat transfer of the molten regolith. The sensible heat transfer data is anticipated to closely correlate a lunar thermal energy storage system. The elemental chemistry of the simulated lunar regolith has been shown by the University of Minnesota to closely correlate to the 10084 soil sample returned on the Apollo 11 mission.

The LUTHER experiment will have the capability for testing varying regolith particles sizes, and densities within the apparatus under vacuum conditions. The melting characteristics of the regolith will be studied in detail for various densities and particle sizes in addition to obtaining data for the thermophysical properties. The melt patterns, and void formations that occur as the regolith changes phase will offer insight to future designs of in-situ thermal energy storage systems.

8.0 REFERENCES

Colozza, A.J. (1991) "Analysis of Lunar Regolith Thermal Energy Storage." November 1991, NASA CR-189073, 2, 2.

Crane, Roger A. (1991) "Evaluation of In-Situ Thermal Energy Storage for Lunar Based Solar Dynamic Systems." March 1991, NASA CR-189054, 19, 40, 40, 40, 41.

Goldich, S.S. (1971) "Lunar and Terrestrial Ilmenite Basalt", Science, 171.

Taylor, S.R. (1975) "Lunar Science: A Post-Apollo View." Pergamon Press, N.Y., pp. 372-73.

Weiblen, P.W. and Morey, G.B. (1980) "Early Lunar Petrogenesis, Oceanic and Extraoceanic." Papike, J.J., Merrill R.B., eds. In Proceedings of the Conference on the Lunar Highlands Crust, 81.

Weiblen, P.W., Murawa, M.J., and Reid, K.J. (1990) "Preparation of Simulants for Lunar Surface Materials." In Proceedings of Space '90 Aerospace/ASCE/Albuquerque, NM, pp. 98-99.

Yoder, H.S. (1976) "Generation of Basaltic Magma", Nation Academy of Sciences, Washington, D.C., pp. 71-72.

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13. ABSTRACT (*Maximum 200 words*)

A Lunar Thermal Energy from Regolith (LUTHER) experiment has been designed and fabricated at the NASA Lewis Research Center to determine the feasibility of using lunar soil as thermal energy storage media. The experimental apparatus includes an alumina ceramic canister (25.4 cm. diameter by 45.7 cm. length) which contains simulated lunar regolith, a heater (either radiative or conductive), 9 heat shields, a heat transfer cold jacket, and 19 type B platinum rhodium thermocouples. The simulated lunar regolith is a basalt, mined and processed by the University of Minnesota, that closely resembles the lunar basalt returned to earth by the Apollo missions. The experiment will test the effects of vacuum, particle size, and density on the thermophysical properties of the regolith. The properties include melt temperature (range), specific heat, thermal conductivity, and latent heat of storage. Two separate tests, using two different heaters, will be performed to study the effect of heating the system using radiative, and conductive heat transfer. The physical characteristics of the melt pattern, material compatibility of the molten regolith, and the volatile gas emission will be investigated by heating a portion of the lunar regolith to its melting temperature (1435 K) in a 10^{-4} pascal vacuum chamber, equipped with a gas spectrum analyzer. A finite differencing SINDA model was developed at NASA Lewis Research to predict the performance of the LUTHER experiment. The analytical results of the code will be compared with the experimental data generated by the LUTHER experiment. The code will predict the effects of vacuum, particle size, and density has on the heat transfer of the simulated regolith.

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